ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

LEC
Laboratory for Energy Conversion

High Brightness LPP Light Source for Inspection Applications in High Volume Manufacturing

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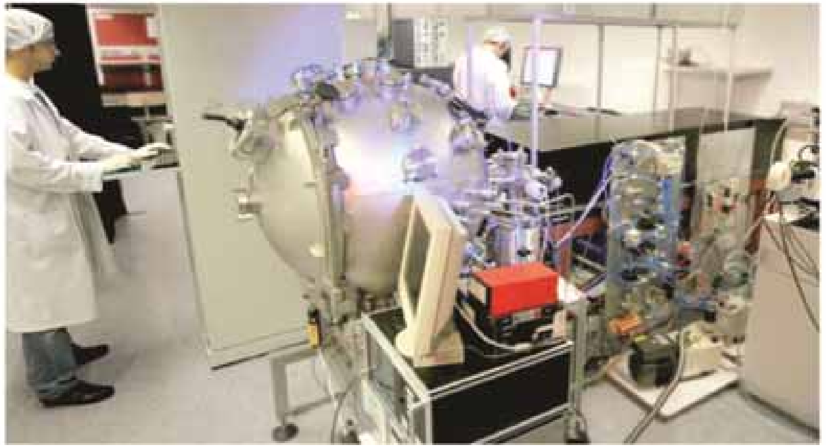
Presentation Outline

- ALPS Facilities
- ALPS II Details
- Droplet Generation and Stability
- Plasma Measurements
- Numerical Simulations of Droplet-based LPPs
- Alternative Fuels
- Summary and Outlook

ALPS Facilities at ETH Zurich

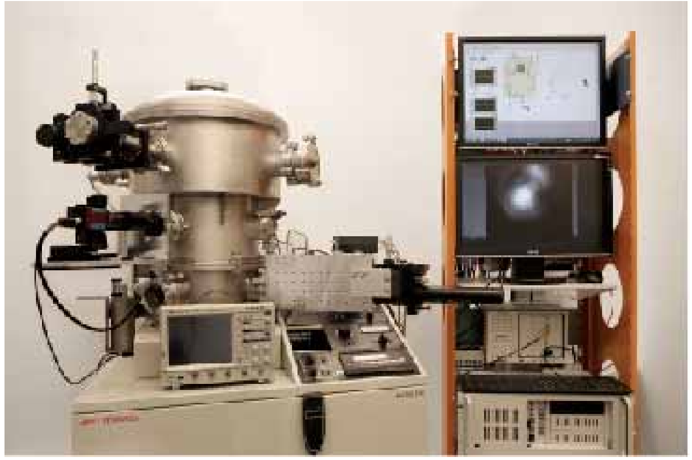
ALPS II (2013)

- High brightness inspection tool for HVM
- Engineering test stand for long-term effects (> 8 hours) studies



ALPS I (2007)

- Plasma physics studies and diagnostics development



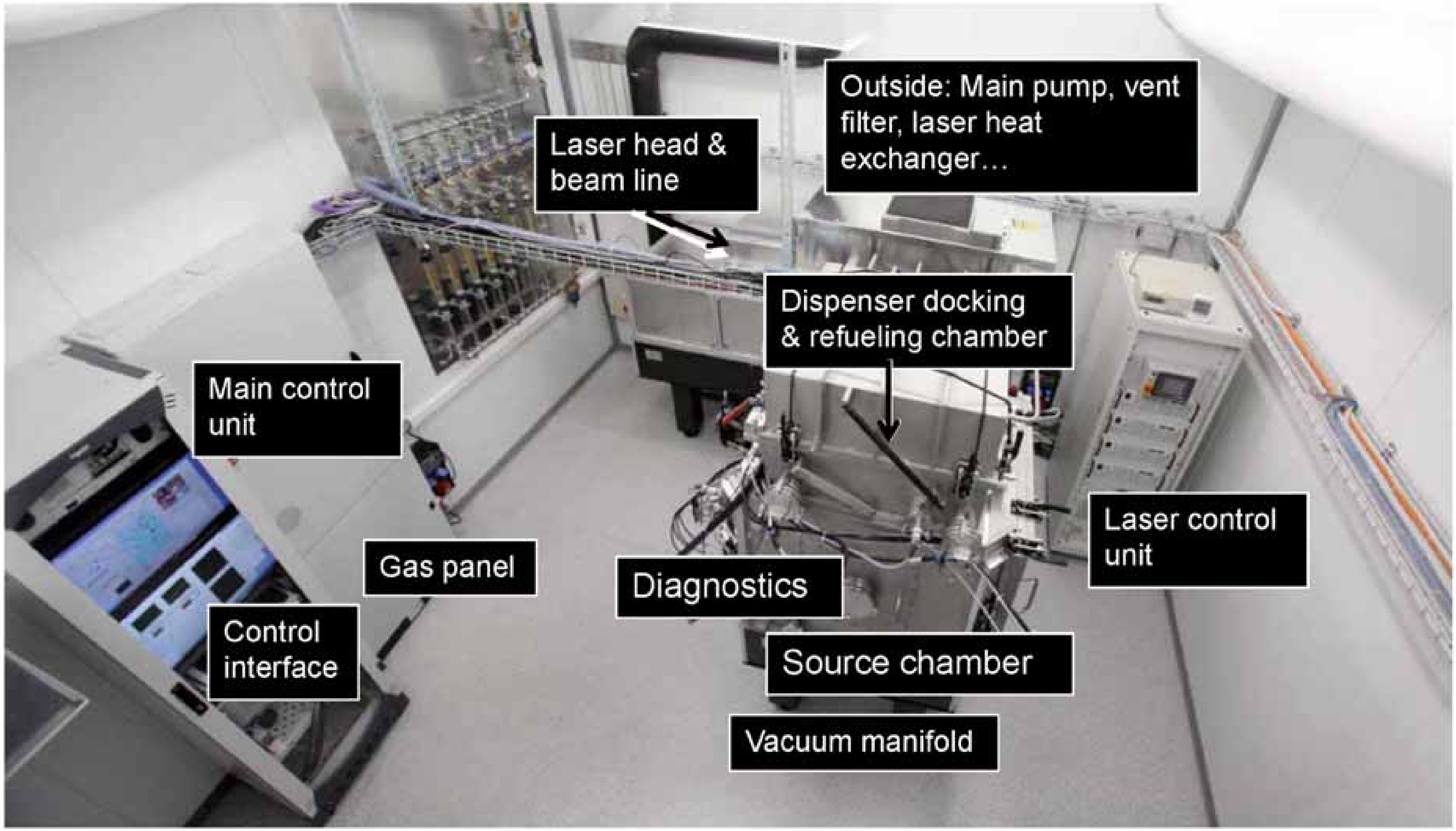
Droplet Dispenser Development Facility (2009)

ALPS II Facility

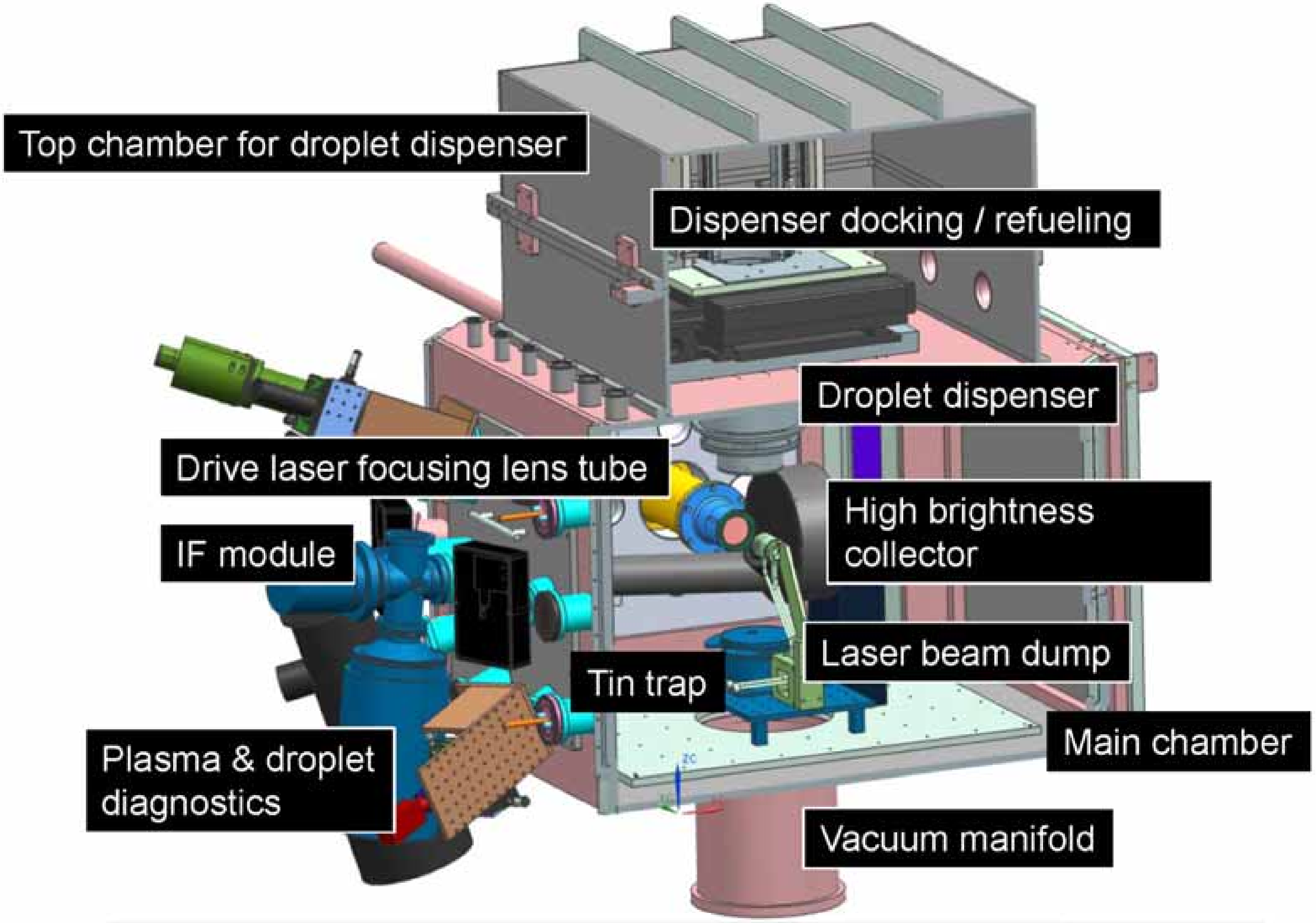
- Newly built lab to accomodate ALPS II facility
- Lab operational since February 2013
- Facility fully operational by July 2013

- 1.6 kW Nd:YAG laser at 1064 nm, up to 20 kHz repetition rate
- Large capacity droplet dispenser, mounted on 3D motion stage
- Droplet tracking system, coupled to x-y motion, with integrated laser triggering
- Different high brightness collector configurations
- Fully automated through single control unit

ALPS II Layout



Source Chamber Layout



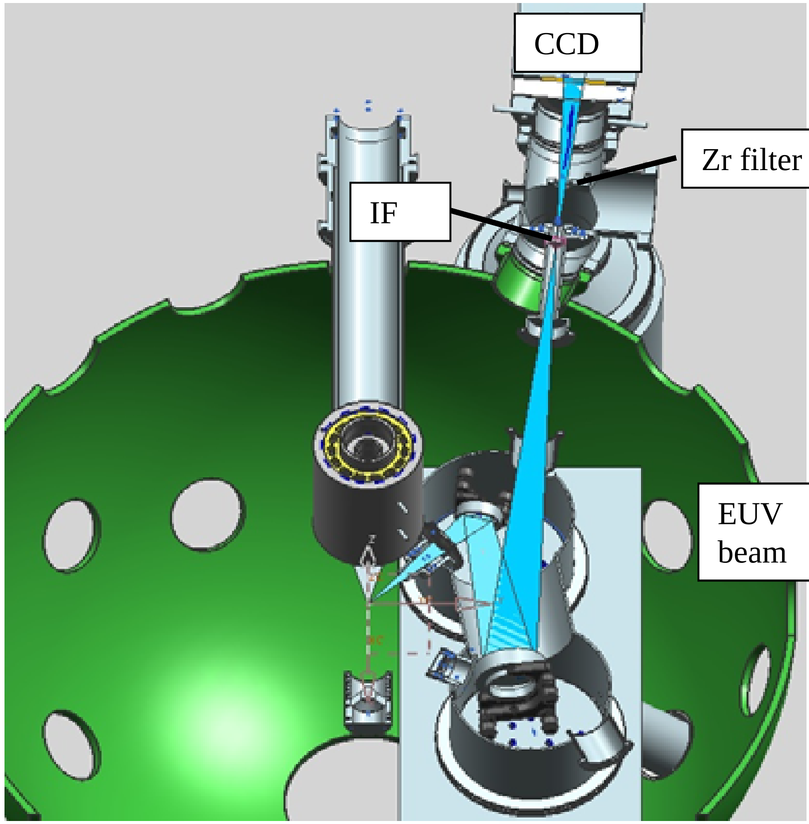
EUV Generation and Collection

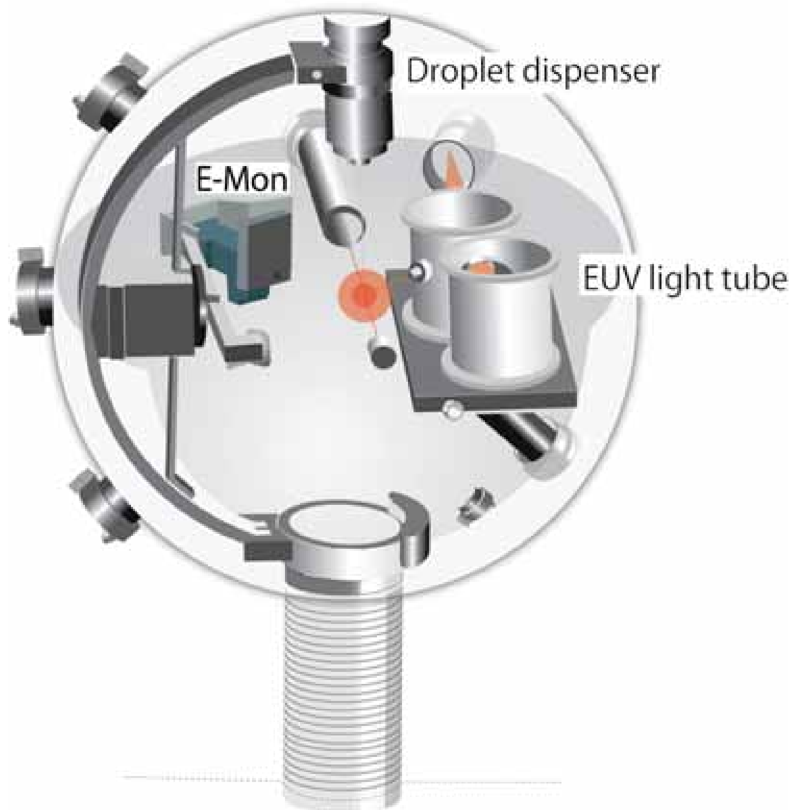
- New high brightness collector for ALPS II with >10x life-time improvement over initial collector
- Inertial debris mitigation optimized for stopping ions and minimizing EUV absorption

Parameters	Value
Laser power on target (W)	1100
Laser Frequency (kHz)	>8
Laser focal spot size (µm)	78 (FWHM)
EUV source size (µm)	95 (FWHM)
Average conversion efficiency (%)	>1%
Collected EUV power (mW)	>35
Life-time increase (baseline initial collector)	>10x
Source brightness (W/mm^{2}sr)	>200

ALPS I with High Brightness Collector

- ALPS I equipped with robotic arm for plasma mapping
- Double bounce (planar and spherical mirrors) multilayer collector
- Multilayers inside enclosure and protected by debris mitigation system

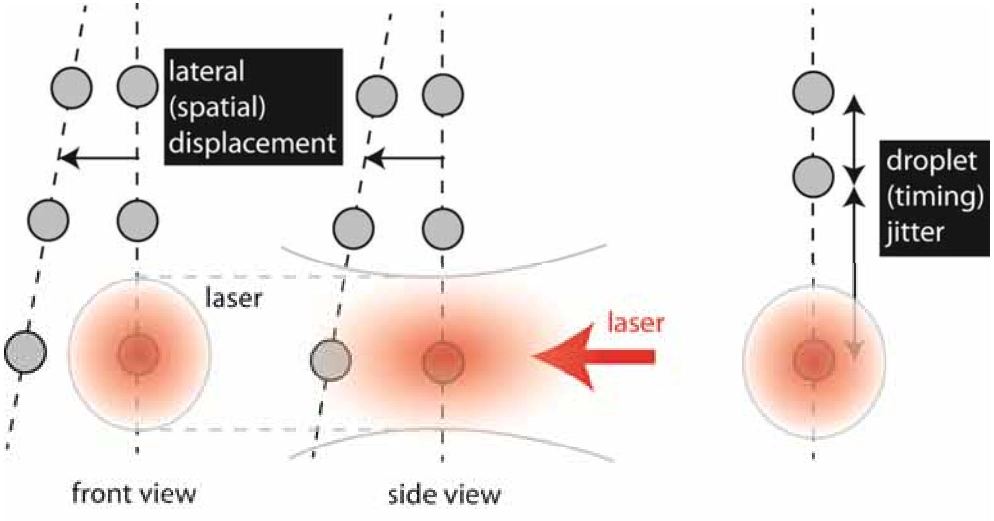


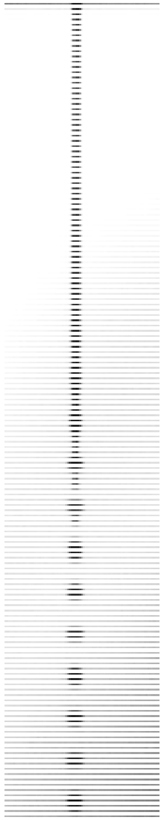


Droplet Generator

- Droplets as a regenerative target can be synchronized with pulsed lasers
- Controlled droplet size reduces debris. Droplet sizes down to 30 µm.
- Droplet dispenser allows operation in range of days.
- 5th version of in-house dispenser in ALPS II with running time of several days

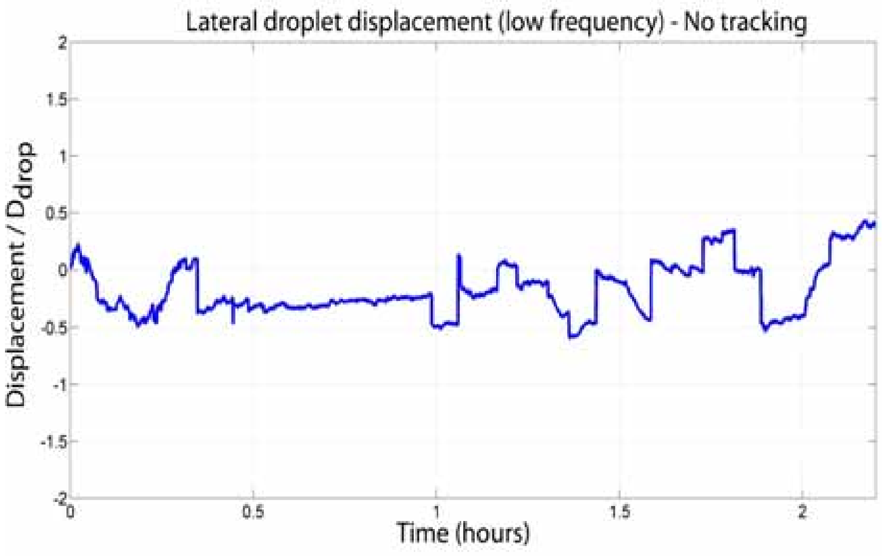
- Droplet stability directly affects source stability, which is a major issue in today's EUV sources

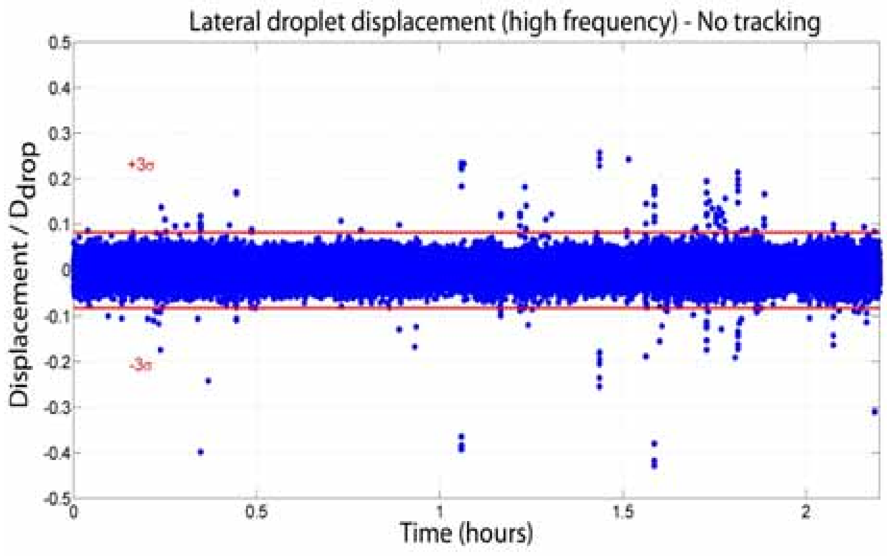




Droplet generation through Rayleigh breakup of a jet (recorded by LEC), close to optimum perturbation wave number

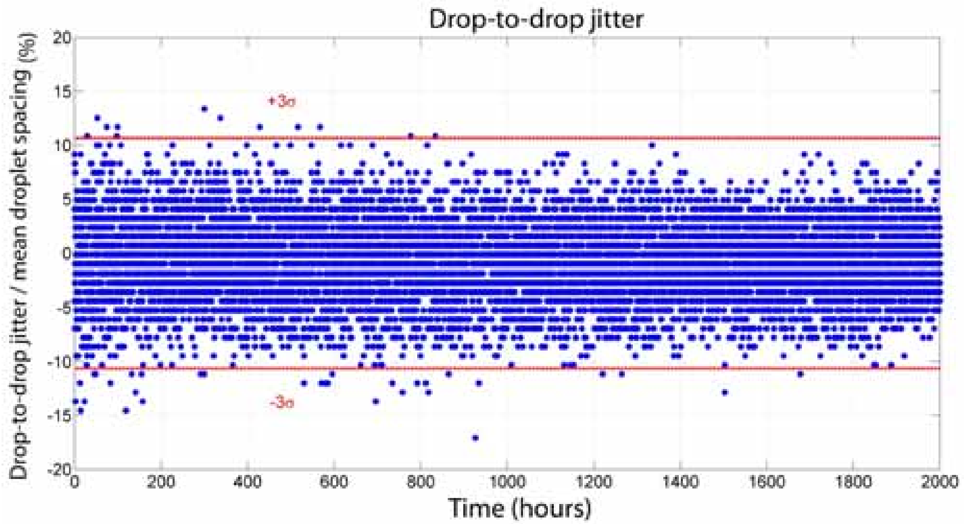
Lateral Droplet Stability

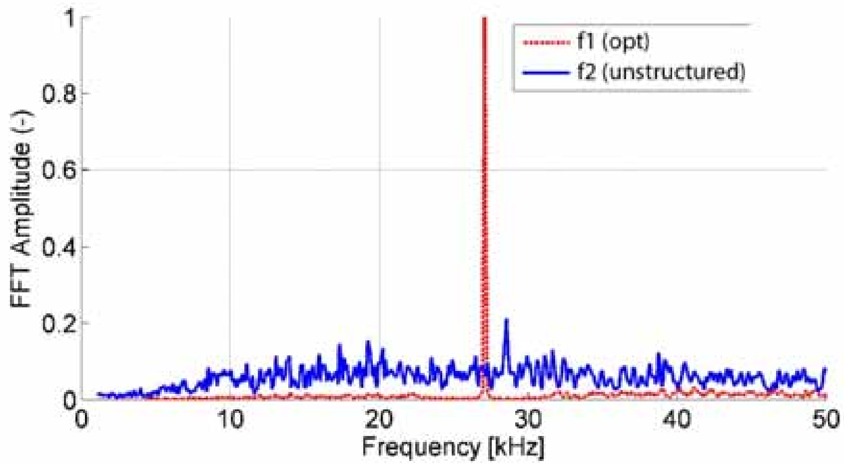




- Lateral droplet displacement is derived from the displacement of the droplet mean line
- High and low frequency separation determined by tracking system
- Low frequency part of the lateral droplet displacement signal varies in a range of 1 droplet diameter
- High frequency part of the droplet displacement signal is equal to 9% of droplet diameter (3σ).

Droplet Timing Jitter

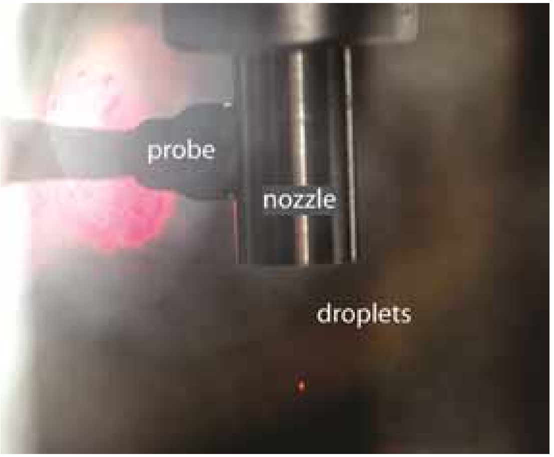




- At operating excitation frequency, low jitter of 10% (3σ) of mean droplet timing interval found.
- Source stability (dose and pulse-to-pulse) increased by individual droplet triggering
- Sensitivity of droplet timing jitter with respect to excitation frequency
- Influence of structural and fluid dynamic resonances on droplet timing

Droplet Research

- Significant research effort into stable generation of micrometer-sized tin droplets



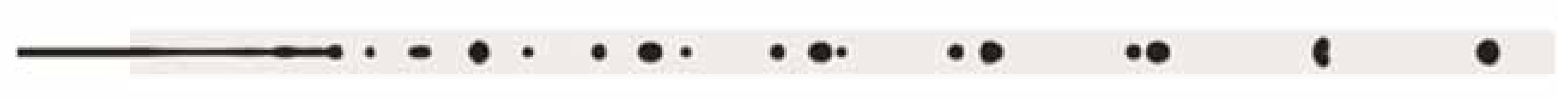
Examples

1. High temperature fast response probe integrated into the dispenser nozzle

Improved understanding of excitation dynamics and boundary conditions for numerical simulations of droplet generation

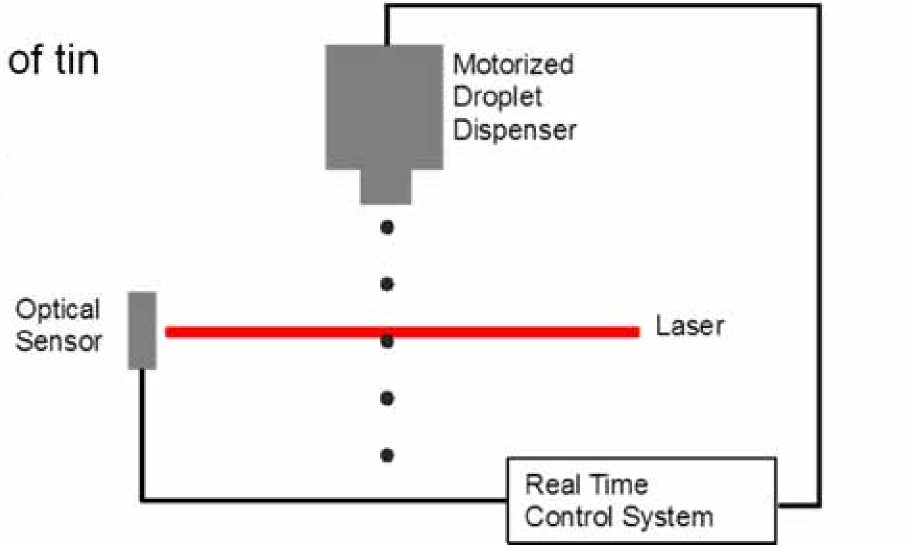
2. Increase of droplet spacing through advanced excitation system

3. Numerical simulation (CFD) of nozzle flow with jet breakup and droplet dynamic

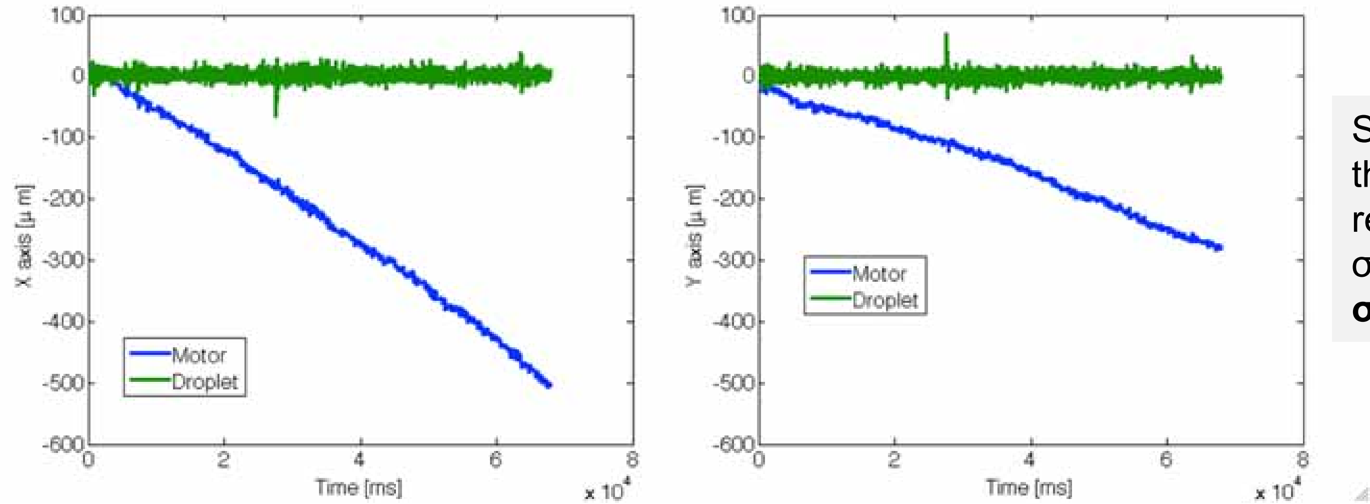


Droplet tracking

- Compensation for low frequency spatial drifts of tin droplet train
- Droplet trace acquisition for triggering system
- EUV signal included in feedback loop
- Spatial resolution: ±5 μm demonstrated
- Temporal resolution: 0.1 s



Droplet position vs. time in the horizontal axes during source operation

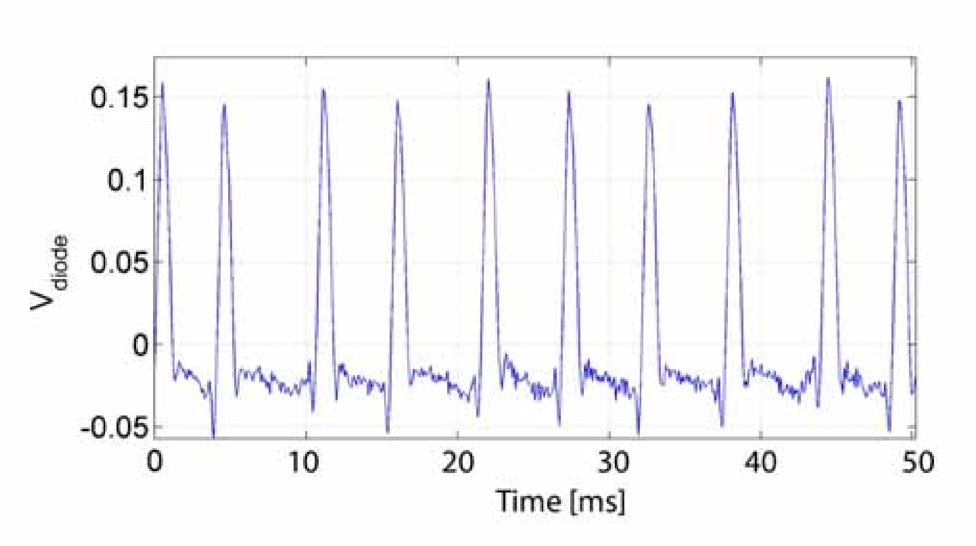


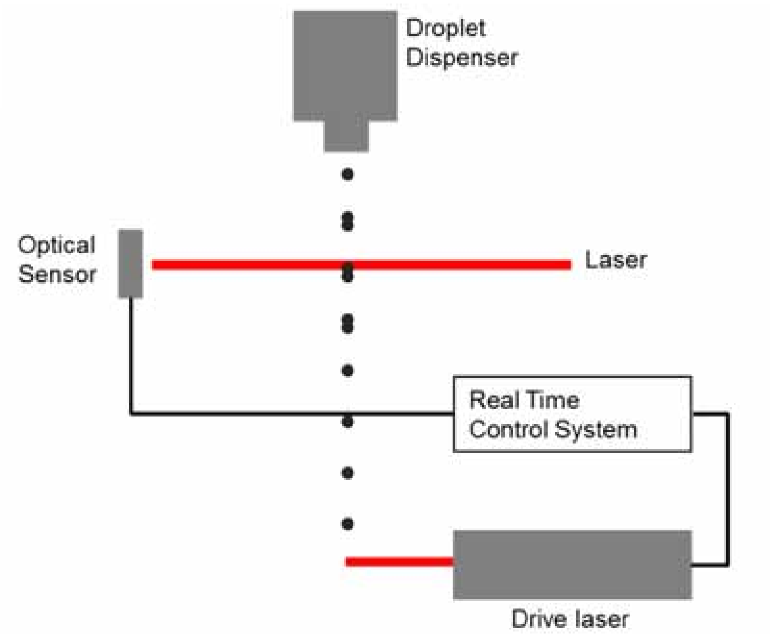
Standard deviation on the droplet position is reduced from σ=150-77μm (ALPS I) to **σ=7.5-6.8μm** (ALPS II)

Droplet triggering

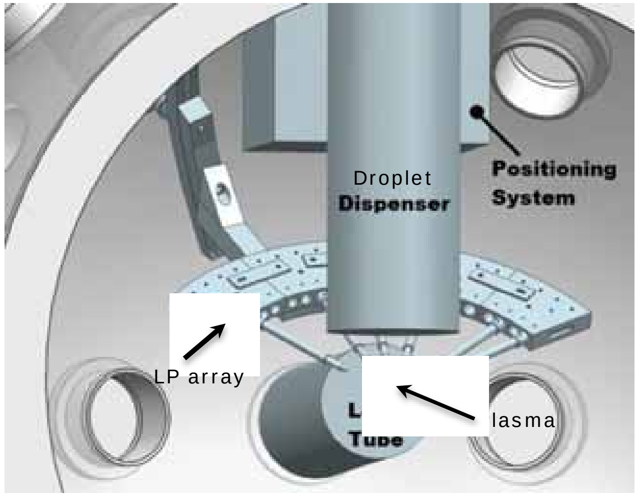
- Compensation of temporal droplet jitter by triggering of laser from individual droplets
- Trigger signal derived from excitation signal with constant time delay yields low pulse-to-pulse emission stability
- Fast computation of prediction of droplet passage at plasma site

Droplet trace vs. time, as used for the triggering system



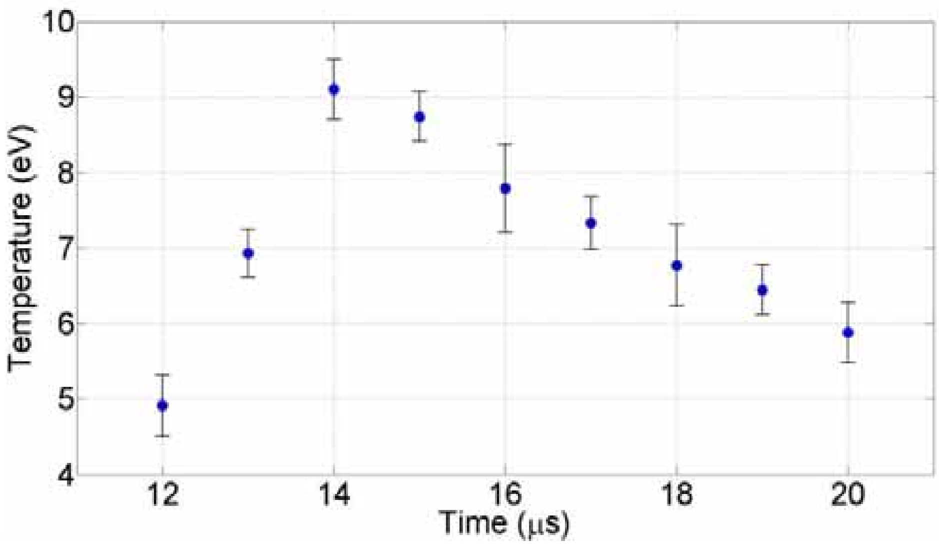


Plasma studies with Langmuir Probes



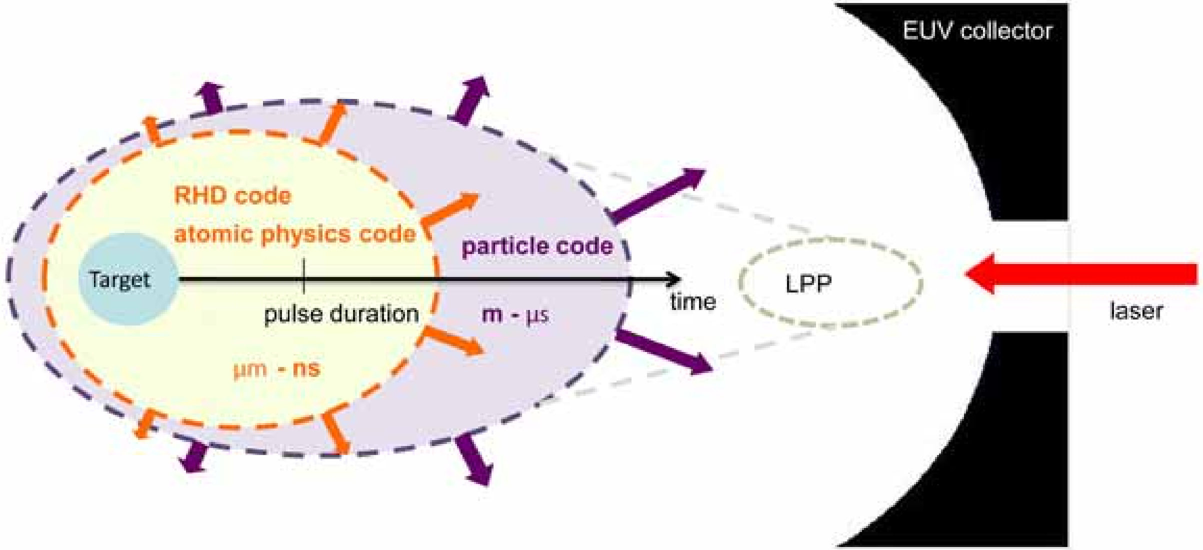
- Determine main plasma parameters at different source operating conditions
- LP's placed at different angles and distances with respect to the droplet target position
- Electron and ion time of flight (TOF) signals of the droplet plasma measured

- Post-processing of the TOF signals, allows derivation of *I-V curves*
- *I-V curve* analysis permits to estimate the plasma parameters (electron density and temperature, plasma potential) in time and space



Multi-scale modeling of droplet-based LPP

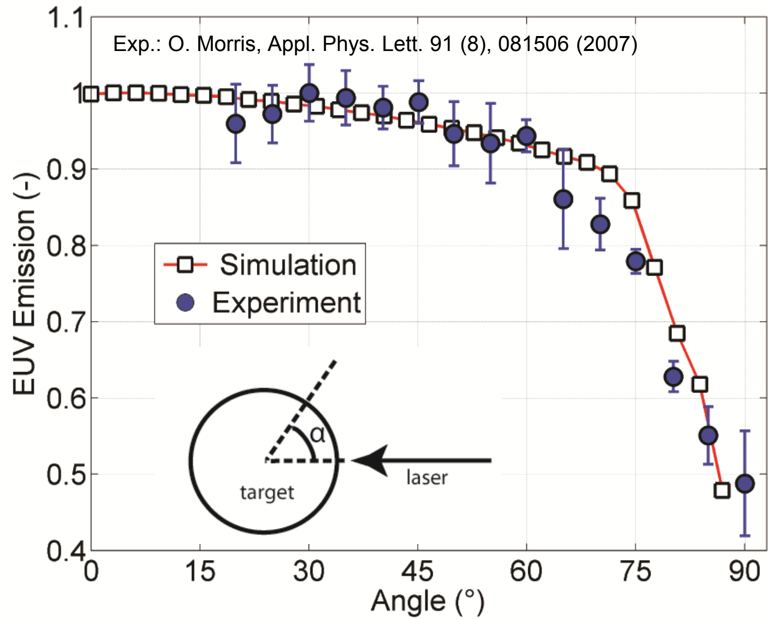
- Physical processes of plasma formation and expansion extend over a large range (typically 6 orders of magnitude) of time and length scales

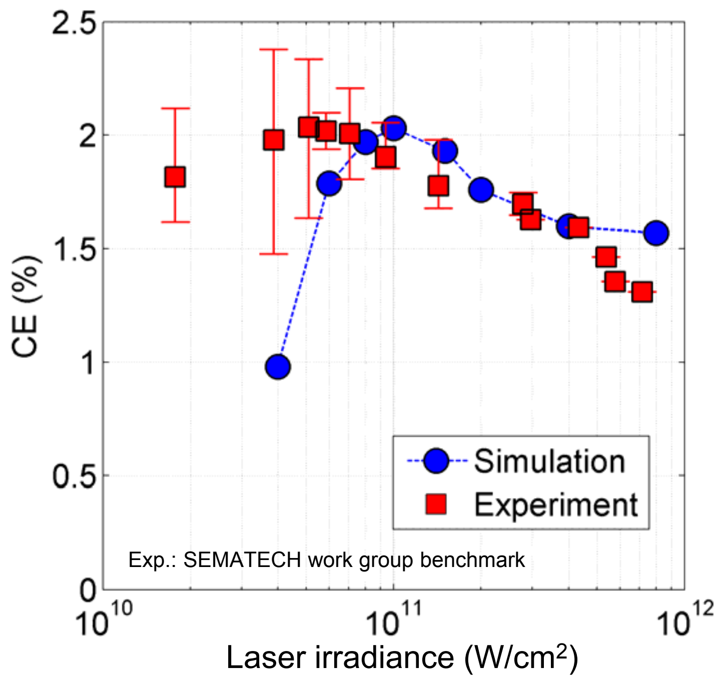


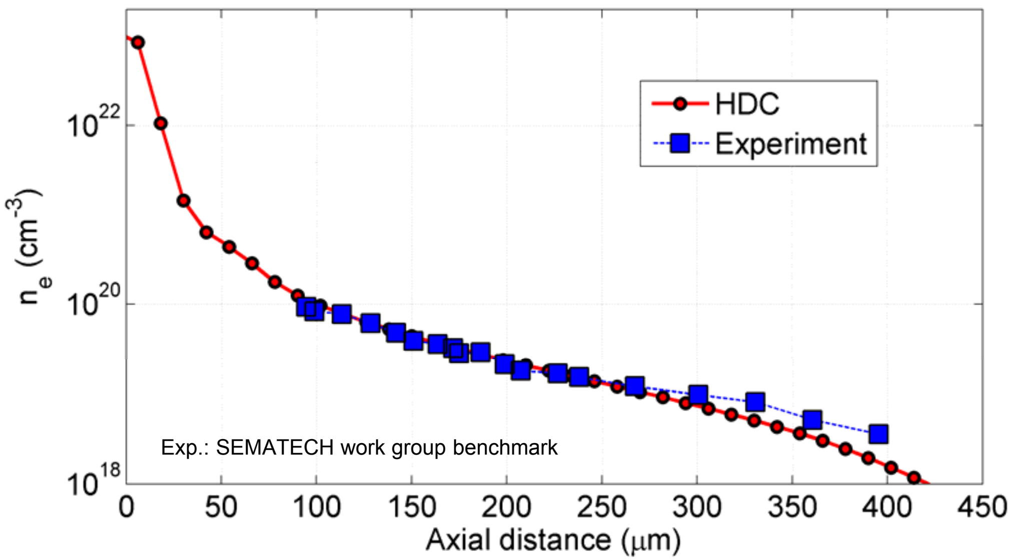
- Early stages of laser-target, laser-plasma interaction modeled using a radiation hydrodynamic (RHD) code, together with atomic physics code for radiation modeling.
- The advanced expansion stages (rarefied flow) are modeled using a combined Particle-In-Cell (PIC, electric / magnetic field modeling) and Direct Simulation Monte Carlo (DSMC, collision modeling) methods, coupled in a hybrid approach to the RHD code.
- An unsteady interface (determined by local degree of rarefaction) transfers boundary conditions from RHD to PIC-DSMC.

Validation of RHD code

- Separate validations of EOS, radiation and hydrodynamic results for planar targets
- Overall good agreement with experimental results
- Additional validations of atomic physics computations (spectra) and particle code predictions

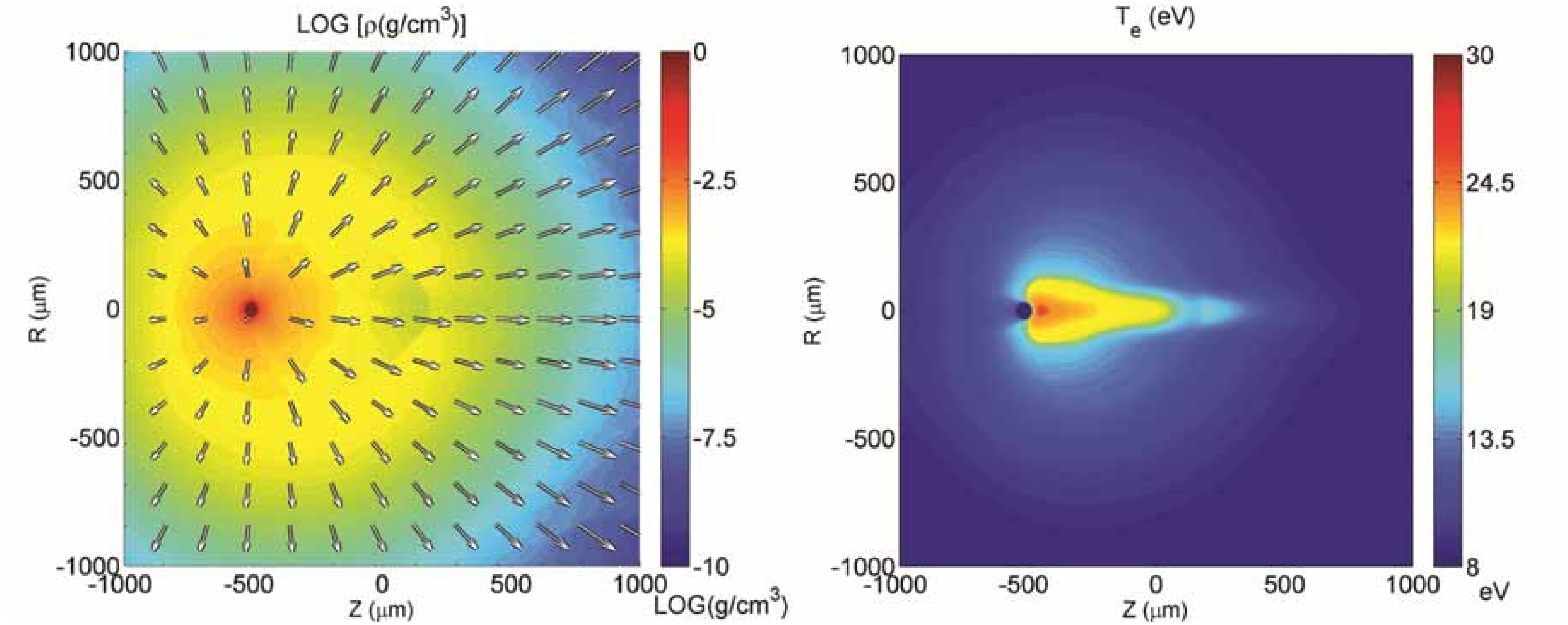






Baseline simulation - Hydrodynamics

- 50 µm pure tin droplet irradiated by 80 µm (FWHM) Nd:YAG (1064 nm), 200 GW/cm^2, 22 ns (FWHM) pulse duration
- Mass density/ velocity (vectors) and el. temperature distributions at 50% pulse duration



- Plasma expansion is not isotropic with largest velocities (E_{kin}) along laxer axis
- Discontinuity in mass density distribution in front of droplet (limited mass supply)
- High temperature region located at critical density, stretched forward towards laser

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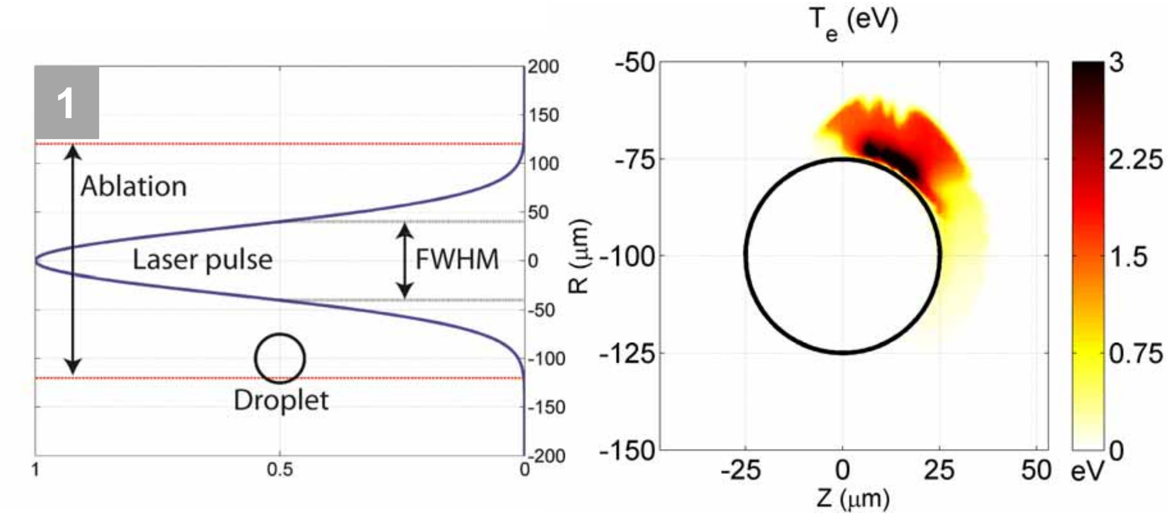
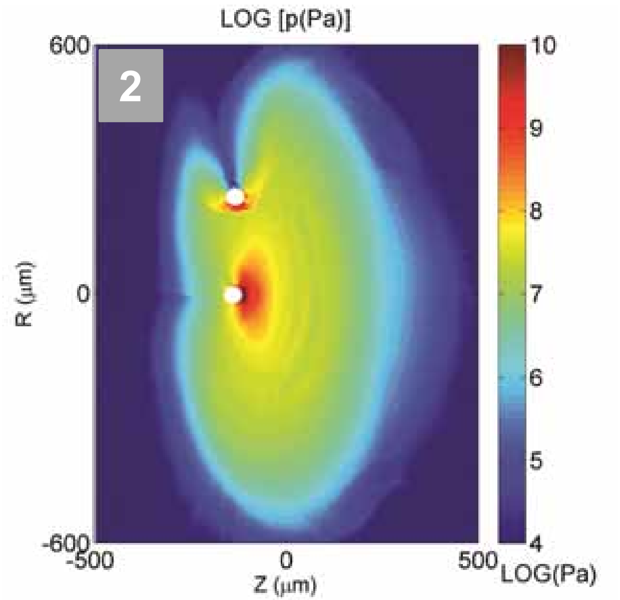
Droplet-based LPP specific studies

- Evaluate impact of experimental misalignments (jitter, lateral displacement) on EUV emission

- Minor fraction of laser energy causes ablation. Plume expands normal to surface and interacts with high energy region of laser.





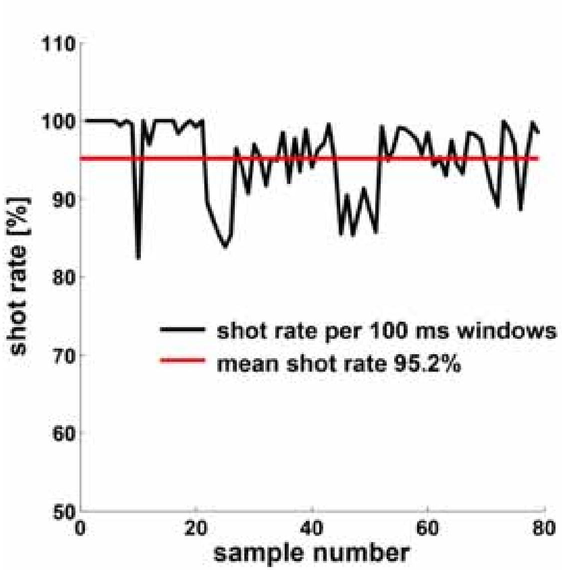
- Study of LPP interaction with subsequent droplet

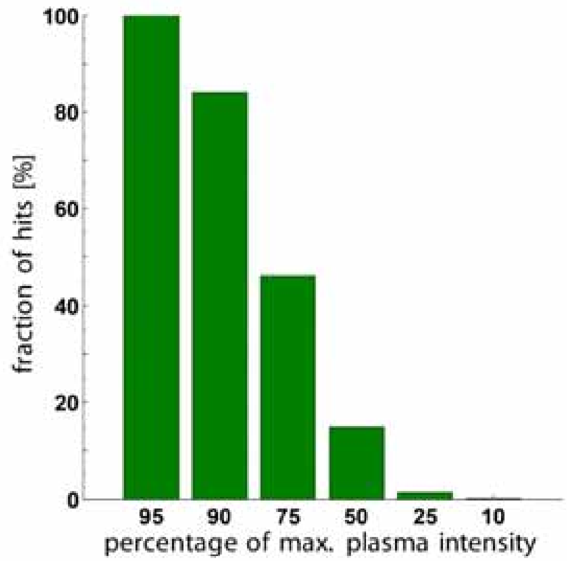
- Around peak laser intensity, net pressures up to 1 GPa are reached for a droplet spacing of 5 droplet diameters.

- Droplet splitting or oscillatory deformations possible. Research focus on maximizing droplet spacing

Alternative Fuels

- ALPS source operated with indium and gallium droplets.
- Gallium used as droplet target for emission at 6.x nm (Doehring *et al.*, 1994). Current source setup yields ion stages up to Ga X (> 16.7 nm).
- Very high initial droplet stability of both alternative fuels, when compared to tin. Hit rates exceeding 95% for Ga, without droplet tracking and drop-by-drop triggering.





Summary

- Fully operational new engineering tool (ALPS II) with goal to enable high throughput and sensitivity/defect capture rate for HVM.
- Two additional fully operating facilities for droplet studies and plasma physics studies (ALPS I).
- Real time closed loop droplet positioning system (with one order of magnitude higher response time) demonstrated.
- Drop-by-drop triggering update in new facility for pulse-to-pulse stability improvement.
- Use of Langmuir probe in droplet-based LPPs. Effort to increase spatial and temporal ranges / resolutions.
- Computational tools predict evolution of LPP over full range of time and length scales.
- New studies on alternative fuels such as Ga and In.